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# Matter and Antimatter in the Universe\*

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## Abstract

We review observational evidence for a matter-antimatter asymmetry in the early universe, which leads to the remnant matter density we observe today. We also discuss bounds on the presence of antimatter in the present day universe, including the possibility of a large lepton asymmetry in the cosmic neutrino background. We briefly review the theoretical framework within which baryogenesis, the dynamical generation of a matter-antimatter asymmetry, can occur. As an example, we discuss a testable minimal particle physics model that simultaneously explains the baryon asymmetry of the universe, neutrino oscillations and dark matter.

## I Introduction

The existence of antimatter is a direct consequence of combining two of the most fundamental known concepts in physics, the theory of relativity and quantum mechanics. Its theoretical prediction, based on these abstract principles [2], and experimental discovery [3] mark one of the great successes of theoretical physics. At the time of its discovery, antimatter was thought to be an exact mirror of matter; all phenomena that had been observed in nature were invariant under conjugation of parity (P) and charge (C) as well as time reversal (T), and not much was known about the early history of the universe. Henceforth, the enormous matter-antimatter asymmetry of the nearby universe (complete absence of antimatter except in cosmic rays) posed a mystery that could only be explained by assuming that the universe was set up like this.

With rise of the big bang theory after the theoretical prediction [4, 5] and observational discovery of the cosmic expansion [6] and microwave background (CMB) [7], it came clear that the universe was hot during the early stages of its history [8], and antimatter was present when pair-creation and annihilation reactions were in thermal equilibrium. When particle energies in the cooling plasma became too small for pair creation to occur, almost all particles and antiparticles annihilated each other, with a small amount of matter (by definition) surviving.

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\*Prepared as invited contribution to [1]

The baryon asymmetry of the universe (BAU) can be defined as the difference between the number of baryons  $N_B$  and antibaryons  $N_{\bar{B}}$  divided by their sum (or the entropy  $s$ ) just before antiprotons disappeared from the primordial plasma. Since the end products of annihilation processes are mostly photons and there are no antibaryons in the universe today<sup>1</sup>, the BAU can be estimated by the baryon to photon ratio  $\eta$ ,

$$\eta = \frac{N_B}{N_\gamma} \Big|_{T=3K} = \frac{N_B - N_{\bar{B}}}{N_\gamma} \Big|_{T=3K} \sim \frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}} \Big|_{T \gtrsim 1\text{GeV}}. \quad (1)$$

In the last term we have expressed the temperature in GeV, with  $1\text{GeV} \simeq 1.16 \cdot 10^{13}\text{K}$ .  $\eta$  is related to the remnant density of baryons  $\Omega_B$ , in units of the critical density, by  $\Omega_B \simeq \eta / (2.739 \cdot 10^{-8} h^2)$ , where  $h$  parameterises the Hubble rate  $H_0 = 100h$  (km/s)/Mpc. It can be determined independently in two different ways, from the abundances of light elements in the intergalactic medium (IGM), see section III.1, and from the power spectrum of temperature fluctuations in the CMB, see section III.2. Both consistently give values  $\eta \sim 10^{-10}$ ; the precise numbers are given in section III. Thus, today's huge matter-antimatter asymmetry was actually a tiny number in the past. The discovery of violations of P [9] and CP [10] invariance (and thus also C invariance) in nature provided hints that this asymmetry may have been created dynamically by *baryogenesis* from a matter-antimatter symmetric initial state.

There are three necessary conditions for successful baryogenesis, which were first formulated by Sakharov [11]<sup>2</sup>: I) baryon number violation, II) C and CP violation and III) a deviation from thermal equilibrium. Intuitively, these conditions can easily be understood. Without baryon number violation, it is not possible for any system to evolve from a state with baryon number  $B = 0$  to a state with  $B \neq 0$ . If C (or CP) symmetry were to hold, for each process that generates a matter-antimatter asymmetry, there would be a C (or CP) conjugate process that generates an asymmetry with the opposite sign and occurs with the same probability. Finally, thermal equilibrium is a time translation invariant state in which the expectation values of all observables are constant, therefore it requires a deviation from equilibrium to evolve from  $B = 0$  to  $B \neq 0$ . Formally, Sakharov's conditions can be proven by means of quantum mechanics and statistical physics. We describe the universe as a thermodynamic ensemble, characterised by a density matrix  $\varrho$ . In the Schrödinger picture,  $\varrho$  evolves in time according to the von Neumann (or quantum Liouville) equation

$$i \frac{\partial \varrho(t)}{\partial t} = [\text{H}, \varrho(t)], \quad (2)$$

where  $\text{H}$  is the Hamiltonian. The baryon number is given by  $B(t) = \text{tr}(\text{B}\varrho(t))$ , where  $\text{B}$  is the baryon number operator. If  $[\text{B}, \text{H}] = 0$  and  $B = 0$  at initial time, then  $B = 0$  at all times, which proves I). To prove II), we consider an arbitrary discrete transformation  $\text{X}$  that commutes with  $\text{H}$  and anticommutes with  $\text{B}$ . If  $\varrho(t)$  at some time  $t_0$  is symmetric under  $\text{X}$ , i.e.  $[\text{X}, \varrho(t_0)] = 0$ , then this holds for all times. Thus, in order to create a CP-asymmetric state from a symmetric initial state,  $\text{H}$  must not commute with CP. The proof of III) is trivial since in thermal equilibrium,  $\varrho^{eq}$  is time translation invariant by definition, thus  $B$  is constant.

The paradigm of *cosmic inflation* [13] elevated the idea of an initial state with  $B = 0$  from an assumption, based on aesthetic reasoning, to a generic prediction. If the universe underwent

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<sup>1</sup>Here we assume that the BAU is the same everywhere in space within the observable universe, we discuss this point in section II.

<sup>2</sup>See also [12] for a related early discussion.

a period of accelerated expansion during its very early history that lasted for long enough to explain its spacial flatness and the isotropy of the CMB temperature, any pre-existing baryon asymmetry was diluted and negligible at the end of inflation<sup>3</sup>. Therefore, baryogenesis needs to occur either during reheating or in the radiation dominated epoch.

The Standard Model of particle physics (SM) and cosmology in principle fulfills all three Sakharov conditions [14]. Baryon number is violated by sphaleron processes [14, 15], P and CP are violated by the weak interaction and the quark Yukawa couplings [16] and the nonequilibrium condition is fulfilled due to the expansion of the universe. As it turns out, the values of the CP-violating Kobayashi-Maskawa phase and mass of the Higgs particle suggested by experiments make it extremely unlikely that successful baryogenesis is possible within the SM. The CP violation and deviation from equilibrium during electroweak symmetry breaking are both too small. These aspects are discussed in more detail in section IV.1. However, models of particle physics beyond the SM generally contain many new sources of CP and possibly  $B$ -violation, and a large number of baryogenesis scenarios is discussed in the literature.

**The remainder of this article is organised as follows.** The following two sections are devoted to observational evidence for a matter-antimatter asymmetry in the universe. In section II we review bounds on the existence of primordial antimatter at present time. We also discuss the possibility that there is no overall asymmetry in the universe, which is composed of regions dominated by matter or antimatter. We conclude that it is almost certain that all structures in the observable universe are composed of matter only<sup>4</sup>. In section III we adopt that viewpoint and review current measurements of the asymmetry parameter defined in (1). In section III we briefly overview theoretical approaches to explain the BAU, focusing on testable models. Finally, in section IV.3, we discuss a minimal model, in which all new particles may be found using present day observational and experimental techniques.

## II Antimatter in the present Universe

The only place in the present day universe where we can directly look for antimatter is the solar system, where we have visited and approached various celestial bodies with spacecraft. It does not contain any significant amount of antimatter<sup>5</sup>. We receive direct probes from other parts of our galaxy in the form of cosmic rays, which have recently been intensely studied by the PAMELA and FERMI space observatories. These contain a fraction of positrons and anti-protons, the only primary source of antimatter found outside the laboratory to date. However, since the pair creation threshold for these particles is relatively low, they can be generated by various astrophysical processes and are expected to be found even in a universe that is entirely made of matter otherwise. If heavier antinucleids were found, this would indicate that there exists traces of antimatter within our own galaxy. So far, none have been discovered. The lack of findings by the first mission of the Alpha Magnetic Spectrometer (AMS) allows to conclude their

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<sup>3</sup>If  $B$  and  $L$  are violated individually, as e.g. in the model presented in section IV.3 or thermal leptogenesis, a state with  $B = 0$  is also reached unavoidably, even for an initial  $B \neq 0$ , when the universe reaches chemical equilibrium.

<sup>4</sup>Here and in the following “matter” and “antimatter” refer to baryons. We do not discuss the unknown composition and origin of dark matter (except in section IV.3), which in many popular models is not related to  $\eta$ .

<sup>5</sup>Antimatter in the solar system can also be excluded because it would lead to a strong signal when annihilating with solar winds [17].

absence at a level of  $10^{-6}$  [20]. These bounds are expected to tighten after data from the AMS 02 experiment, currently mounted on the International Space Station, is released. Furthermore, in [19] it was argued that the fraction  $f$  of antimatter in the ISM cannot be larger than  $f < 10^{-15}$  because the lifetime of antinuclei in the ISM due to annihilations is only 300 years [17].

Upper bounds on the presence of antimatter in other parts of the universe can be imposed by indirect detection methods. One can distinguish two basic scenarios: Either matter and antimatter are mixed homogeneously, i.e. the interstellar medium (ISM) or IGM are matter dominated everywhere in space, but contain a certain fraction of antimatter<sup>6</sup>, or patches of matter and antimatter coexist. In both cases one would expect to observe X-rays and  $\gamma$ -rays from annihilation processes.

## II.1 A Patchwork Universe

If the universe is a patchwork of regions that are strongly dominated either by matter or antimatter, the question arises what is the typical size of such regions. The possibility of individual antimatter stellar systems has been discussed in [17, 19], see also [18]. The absence of annihilation signals from such stars passing through the ISM allows to conclude that their fraction in the galaxy is  $< 10^{-4}$ . Since the presence of such systems is hard to accommodate within a realistic model of galaxy formation, it is tempting to conclude that it is zero. Similar arguments can be brought forward against the possibility of clouds of anti-gas or other isolated objects in the milky way. This viewpoint has been questioned in [21], see also references therein. However, no definite conclusions that hint towards the opposite could be drawn. In [19] it was furthermore pointed out that the authors of [21] may have underestimated the annihilation cross sections at low energies.

This still leaves open the possibility that the universe is a patchwork of huge distinct regions of matter and antimatter, in the most extreme case with vanishing baryon number  $B = 0$  when averaged over large volumes. If this were the case, these regions would have to be at least of comparable size as the observable universe [22, 23]. This conclusion can be drawn from the measured cosmic diffuse  $\gamma$ -ray (CDG) background. After nonlinear structure formation, the matter and antimatter domains may have been separated by sufficiently large voids in the IGM to suppress annihilation at the domain walls and avoid a detectable  $\gamma$ -ray flux. However, the homogeneity of the CMB does not allow for such spacial separation before recombination. Hence, matter and antimatter domains must have been in touch at least between the time of recombination and the beginning of nonlinear structure formation. The  $\gamma$ -rays produced by annihilation during this period would, though redshifted, still be present today and contribute to the CDG. The measured intensity of the CDG allows to conclude that the domains must at least have a size comparable to the observable universe [22].

## II.2 A mixed Universe

The considerations at the beginning of this section strongly constrain diffuse antimatter within our galaxy. The fraction  $f$  of antimatter on larger scales is constrained by the measured  $\gamma$ -ray flux from the IGM. The IGM emits X-rays due to thermal bremsstrahlung in 2-body collisions. The expected flux of  $\gamma$ -rays  $F_\gamma$  is proportional to the flux of X-rays  $F_X$ . This allows to constrain

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<sup>6</sup>Such a mixing is not possible within individual stellar systems because the antimatter would have annihilated during the gravitational collapse that lead to their formation [17].

$f$  as [19]

$$f \leq 3 \cdot 10^{-11} \frac{T}{\text{keV}} \frac{F_\gamma}{F_X}, \quad (3)$$

where  $T$  is the gas temperature and the inequality is due to the fact that not all  $\gamma$ -rays originate from annihilations. In [19], the upper bounds on the  $\gamma$ -flux imposed by the EGRET space telescope [25] were used to constrain  $f$  for a sample of 55 galaxy clusters from the limited flux survey published in [26]. The obtained values scatter between  $f < 5 \cdot 10^{-9}$  and  $f < 10^{-6}$ , indicating that these clusters consist either entirely of matter or antimatter in good approximation. Furthermore, if there are any antimatter dominated regions, they must be separated from the matter domains at least by distances comparable to the size  $\sim \text{Mpc}$  of galaxy clusters. Observations of colliding galaxy clusters allow to extend the analysis to even larger scales. For the bullet cluster [27], an upper bound of  $f < 3 \cdot 10^{-6}$  was obtained in [19]. If representative, this allows to extend the constraints on  $f$  to scales of tens of Mpc. In combination with the considerations in section II.1 this indicates that the present day observable universe most likely does not contain significant amounts of antimatter.

### III The Baryon Asymmetry of the Universe

As motivated by the discussion in section II, we in the following adopt the viewpoint that the universe is baryon-asymmetric and the asymmetry is the same everywhere within the observable Hubble-volume. Within the concordance model of cosmology ( $\Lambda\text{CDM}$ ) [24] it can be estimated by the baryon to photon ratio (1). There are two independent ways to determine this parameter, from the relative abundances of light elements in the IGM on one hand and from the spectrum of temperature fluctuations in the CMB on the other. Since they measure  $\eta$  at very different stages during the history of the universe, they also provide a check for the  $\Lambda\text{CDM}$  model itself.

#### III.1 Big Bang Nucleosynthesis

Throughout the evolution of the universe, there was a brief period during which the temperature was low enough for nuclei with mass number  $A > 1$  to exist and still high enough for thermonuclear reactions to occur. This *big bang nucleosynthesis* (BBN) is thought to be the main source of deuterium (D), helium ( $^3\text{He}$ ,  $^4\text{He}$ ) and lithium (mainly  $^7\text{Li}$ ) in the universe [8], see e.g. [28] for a review. These elements, in particular H and  $^4\text{He}$ , make up the vast majority of all nuclei in the universe<sup>7</sup>.

The processes relevant for BBN start when the temperature of the primordial plasma is around  $T \sim 2 \text{ MeV}$  with the neutrino freezeout, i.e. the reactions that keep neutrinos in equilibrium with the plasma become slower than the expansion of the universe. This energy range is easily accessible in the laboratory, and the underlying particle physics is well-understood. Thus, in the standard scenario the sole unknown parameter that enters BBN is the baryon to photon ratio  $\eta$ , which was fixed by unknown physics (baryogenesis) at higher energies. For given  $\eta$ , the time evolution of the different isotopes' abundances can be determined by solving a network of Boltzmann equations. Thus, within  $\Lambda\text{CDM}$  and the SM,  $\eta$  can be uniquely determined by

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<sup>7</sup>Heavier nuclei are not produced during BBN due to the absence of stable nuclei of mass number 5 and 8 and the bigger Coulomb repulsion between for charge numbers  $Z > 1$ . They can be made in stars (up to iron) or supernovae.

measuring the primordial abundances of light elements. The result found in [29], in units of  $10^{-10}$ , is

$$\eta_{SBBN} = 5.80 \pm 0.27, \quad (4)$$

more constraining than the 95% CL value  $4.7 < \eta_{SBBN} < 6.5$  quoted in [28].

The good agreement with observational data allows to impose tight constraints on theories of particle physics beyond the SM which predict charged or unstable thermal relics from earlier epoch to be present around the time of BBN. Even without additional particles that participate in BBN reactions, non-standard physics may leave a trace in the abundances of light elements by modifying the expansion rate of the universe. The expansion rate is given by

$$H^2 = \frac{8\pi}{3}G\rho, \quad (5)$$

where  $G$  is Newton's constant,  $H$  the Hubble parameter and  $\rho$  the energy density of the universe. In the radiation dominated era at the time of BBN  $\rho \simeq \rho_\gamma + \rho_e + N_\nu \rho_\nu$ , where the first two terms are the energy densities for photons and electrons/positrons and  $\rho_\nu$  is the contribution from a flavour of neutrinos.  $N_\nu$  is the *effective number of neutrino species*. In the standard scenario  $N_\nu = 3$  during BBN<sup>8</sup>. Any deviation  $\Delta N_\nu$  from that can be used to parameterise a non-standard expansion rate. Despite the name, a  $\Delta N_\nu \neq 0$  need not be caused by an additional neutrino species. It may e.g. be due to any non-standard energy budget, gravitational waves, varying coupling constants or extra dimensions. A best fit to the observed element abundances with  $N_\nu$  left as a free parameter, reported in [29], yields

$$\eta_{BBN} = 6.07 \pm 0.33, \quad \Delta N_\nu = 0.62 \pm 0.46, \quad (6)$$

with  $\Delta N_\nu$  consistent with zero at  $\sim 1.3\sigma$ .<sup>9</sup> However, the precise values of these parameters are affected by the selection of datasets and estimates of systematic errors, cf. discussion in [28].

The main uncertainty results from the difficulty to measure the primordial abundances of light elements. They differ from present day values within galaxies, which have been modified by thermonuclear reactions in stars throughout the past 13 Gyrs.  $N_\nu$  is mainly sensitive to the  $^4\text{He}$  abundance (because the expansion history determines the point of neutron freezeout, which affects the neutron fraction  $n/p$  in the plasma),  $\eta$  is sensitive to D. In contrast to He, there are no known astrophysical sources of D [35], thus the observed abundance provides a reliable lower bound on the primordial value. In fact, the BBN bounds on  $\eta$  are almost entirely derived from the D abundance. This has earned D the label "baryometer" of the universe, and the strong dependence on D is the reason why  $\eta$  is relatively insensitive to the infamous  $^7\text{Li}$  problem [30]. It is believed that the most precise measurement to date can be obtained from high redshift low metallicity quasar absorption systems (QSO), though the systematic errors are not fully understood, cf. discussion and references in [28].

### III.2 CMB and LSS

The baryon content of the universe can also be determined from the power spectrum of temperature fluctuations in the CMB. The temperature fluctuations were generated by acoustic oscillations of the baryon-photon plasma in the gravitational potential caused by small inhomogeneities

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<sup>8</sup>At the time of CMB decoupling  $N_\nu = 3.046$  in the SM, where the deviation from 3 parameterises a deviation from the equilibrium distribution of neutrinos caused by  $e^\pm$  annihilation [31].

<sup>9</sup>Recently evidence from different sources that hints towards  $\Delta N_\nu > 0$  after BBN has mounted [32–34], but the statistical significance does not allow a definite conclusion at this stage.



in the DM distribution. The oscillations are sensitive to  $\eta$  because the baryon fraction determines the equation of state of the plasma, which mainly manifests in the relative height of odd and even peaks in the power spectrum. Since the decoupling of photons happens at a vastly different epoch ( $T \sim 0.3$  eV) and the physics that produces the acoustic peaks in the power spectrum is very different from BBN, this is a truly independent measurement. The WMAP7 data [34] alone gives, in units of  $10^{-10}$ ,

$$\eta_{CMB} = 6.160^{+0.153}_{-0.156}. \quad (7)$$

When the WMAP7 data is combined with large scale structure (LSS) data [36] and the Hubble rate  $H_0 = 74.2 \pm 3.6 \text{ km s}^{-1} \text{ Mpc}^{-1}$  found in [38], this value slightly changes to  $\eta_{CMB/LSS} = 6.176 \pm 0.148$  [34]. A similar analysis, combining different CMB and LSS data sets, was performed in [39] and gave results scattered between 6.1 and 6.16 for  $\eta$  in units of  $10^{-10}$ . In the context of baryogenesis,  $\mathcal{O}[1]$  corrections to the above numbers are of little relevance, given our lack of knowledge of physics beyond the SM. The impressive agreement between BBN and CMB results for  $\eta$ , however, is an important hint that we can reliably determine the magnitude of the BAU observationally.

### III.3 A large Lepton Asymmetry?

The good agreement between CMB and BBN results strongly constrains the BAU to be as small as  $\eta \sim 10^{-10}$ . Compared to that, bounds on a lepton asymmetry of the universe (LAU), hidden in the cosmic neutrino background (CNB), are much weaker. The only source of B-violation in the SM are sphaleron processes [14, 15], which are highly inefficient below  $T_{EW} \sim 140$  GeV, as it would be suggested by a 126 GeV Higgs mass [37]. However, if neutrinos are Majorana particles, the Majorana mass term can lead to lepton number violating processes at much lower energies. Furthermore, neutrino mixing may add another source of CP-violation to the SM. Thus, it is possible to imagine nonequilibrium processes that generate a LAU below the electroweak scale that is orders of magnitude larger than the BAU. Though of little effect today, a large lepton asymmetry may have far-reaching consequences in the past. It can trigger a resonant production of dark matter (DM), see section IV.3, or affect the nature of the QCD transition [50].

The main constraints on the LAU come from BBN. It affects BBN in two ways. On one hand, non-zero chemical potentials modify the momentum distribution of neutrinos. This changes the temperature dependence of the energy density and thereby the expansion history. More importantly, electron neutrinos  $\nu_e$  participate in the conversion processes that keep neutrons and protons in equilibrium. The change in the freezeout value of  $n/p$  caused by a  $\nu_e$  asymmetry leaves an imprint in the  $^4\text{He}$  abundance.

The LAU has been studied by different authors [40–42]. It can be defined in analogy to (1),

$$\eta_\alpha = \frac{N_{\nu_\alpha} - N_{\bar{\nu}_\alpha}}{N_\gamma} \Big|_{T=3K}. \quad (8)$$

In absence of neutrino masses, there would be only weak constraints on  $|\eta_\mu|, |\eta_\tau| \lesssim 2.6$  (in units of one!) [41] because at the time of BBN, electrons are the only charged leptons in the primordial plasma.  $\eta_e$  would be constrained to  $-0.012 \lesssim \eta_e \lesssim 0.005$  due to its effect on  $n/p$ . However, neutrino oscillations tend to make the lepton asymmetries in individual flavours equal<sup>10</sup> well

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<sup>10</sup>This process is sometimes referred to as “flavour equilibration”, though the neutrino distribution functions may deviate from Fermi-Dirac because the process occurs close to the neutrino freezeout and neutrinos may not

before BBN [43–45] for values of the neutrino mixing angle  $\theta_{13}$  suggested by experiment [46]. They tie the bounds for all flavours together and introduce a dependency on the choice of mass hierarchy and  $\theta_{13}$ . For  $\sin^2 \theta_{13} = 0.04$ , at the upper end of the region suggested by [51] and about twice the value found more recently in [47–49], the bounds found in [41] are  $-0.17 \lesssim \eta_{e,\mu,\tau} \lesssim 0.1$  for normal and  $-0.1 \lesssim \eta_{e,\mu,\tau} \lesssim 0.05$  for inverted hierarchy. For inverted hierarchy, the dependence on  $\theta_{13}$  is weak, while for normal hierarchy values as large as  $|\eta_{e,\mu,\tau}| \simeq 0.6$  are allowed for small  $\theta_{13}$ . In [42], stronger bounds  $-0.071 < \eta_{e,\mu,\tau} < 0.054$  were found for  $\sin^2 \theta_{13} = 0.04$ , assuming normal hierarchy, and it was pointed out that future CMB observations may be able to compete with BBN in constraining  $\eta_\alpha$ .

## IV Testable Theories of Baryogenesis

### IV.1 Baryogenesis in the SM

In principle, the Sakharov conditions I) - III) are all fulfilled in the SM. This is rather obvious for the conditions conditions II) and III). The weak interaction violates P-invariance maximally, while CP-invariance is violated by the complex phase  $\delta_{KM}$  in the Cabibbo-Kobayashi-Maskawa matrix. The expansion of the universe brings the primordial plasma out of thermal equilibrium. The violation of baryon number, condition I), occurs more subtly<sup>11</sup>.

At the perturbative level, there are four conserved fermion numbers in the SM: The baryon number  $B$  and three lepton numbers  $L_\alpha$ . The observed neutrino oscillations, which cannot be explained within the SM, clearly violate the individual lepton numbers  $L_\alpha$ . If neutrinos are Majorana particles (as e.g. in the model presented in section IV.3), the Majorana mass term also violates the total lepton number  $L = \sum_\alpha L_\alpha$ . Baryon number  $B$  is conserved at each order in perturbation theory, but violated by non-perturbative effects [15]. This can be seen by looking at the baryonic current  $j_\mu^B$ .  $j_\mu^B$  is conserved classically, but obtains a non-zero divergence by a quantum anomaly [54],

$$\partial^\mu j_\mu^B = \frac{n_f}{32\pi^2} (-g^2 \text{tr}(F_{\mu\nu} \tilde{F}^{\mu\nu}) + g'^2 F'_{\mu\nu} \tilde{F}'^{\mu\nu}), \quad (9)$$

where  $g$ ,  $F_{\mu\nu}$  and  $g'$ ,  $F'_{\mu\nu}$  are the gauge coupling and field strength tensor of the SU(2) and U(1) gauge interaction, respectively, and  $n_f = 3$  is the number of fermion families. Baryon number violation is most easily explained semi-classically by *fermionic level crossing* [55, 56]. In the bosonic sector of the standard electroweak theory, there is an infinite number of field configurations that minimise the static energy functional, which we refer to as “vacua”. They are physically equivalent, but can be distinguished by the Chern-Simons number  $N_{CS}$  of the gauge field configuration. The energy levels of fermions depend on the bosonic background fields. Fermionic level crossing occurs when  $N_{CS}$  changes; then an energy level raises above (or falls below) the surface of the Dirac sea, see figure 1, which means that fermions are created (or absorbed) by the background. All SU(2) doublets are subject of level crossing, leading to the simultaneous creation (or disappearance) of 9 quarks and 3 leptons. Thus,  $L_\alpha - \frac{B}{3}$  remain conserved in sphaleron processes though  $B$  and  $L_\alpha$  are violated individually. The different vacua are separated by a potential barrier, the height of which can be estimated by the *sphaleron* energy

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reach thermal equilibrium. This means that a lepton asymmetry cannot be translated into a chemical potential in the strict sense.

<sup>11</sup>See [52] for a pedagogical discussion.



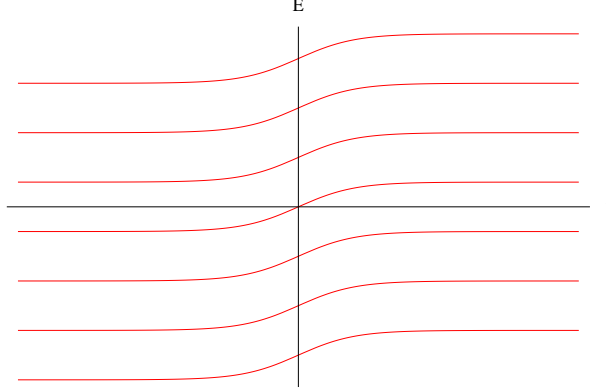


Figure 1: An illustration of fermionic level crossing: The changing bosonic background fields can modify the fermionic energy levels, leading to fermion number violation when a level raises above the surface of the Dirac sea.

$M_{\text{sph}} \sim M_W/\alpha_W$ . The sphaleron is the field configuration of maximal energy along the path of minimal energy in field space that connects two minima in the classical potential [57].

In quantum field theory, the early universe can be described as a thermodynamic ensemble characterised by a density matrix  $\varrho = \exp(-H/T)$ , where  $H$  is the Hamiltonian. At low temperatures  $T \ll T_{EW}$ , only configurations with field expectation values near the minima of the effective potential are significantly populated. Tunneling through the potential barrier is the only process that can change  $N_{CS}$  from such an initial state. The tunneling rate at  $T = 0$  [15] is suppressed by  $\exp(-\frac{4\pi}{\alpha_W}) \sim 10^{-160}$ , effectively forbidding  $B$ -violation in vacuum. Near  $T \sim T_{EW}$  the Boltzmann suppression  $\exp(-H/T)$  is less efficient and  $N_{CS}$  can change by a classical transition due to thermal fluctuations. The probability for these baryon number violating processes is governed by the sphaleron rate [53]

$$\Gamma_{\text{sph}} \equiv \lim_{t, V \rightarrow \infty} \frac{(N_{CS}(t) - N_{CS}(0))^2}{Vt} = \int d^4x \langle \partial^\mu j_\mu^B(x) \partial^\nu j_\nu^B(0) \rangle, \quad (10)$$

where  $V$  is the total volume. The (finite temperature) effective potential and sphaleron configuration change in the vicinity of the electroweak symmetry restoration. In the Higgs phase,  $\Gamma_{\text{sph}}$  is given by

$$\Gamma_{\text{sph}} = A (\alpha_W T)^4 \left( \frac{M_{\text{sph}}}{T} \right)^7 \exp \left( - \frac{M_{\text{sph}}}{T} \right) \quad (\text{Higgs phase}), \quad (11)$$

where  $A$  is a coefficient that can be determined numerically [62–73]. For  $T \gg T_{EW}$ , in the symmetric phase, the Boltzmann suppression is cancelled because  $M_W$  in  $M_{\text{sph}}$  is replaced by the non-abelian magnetic screening scale  $\sim \alpha^2 T$  and  $\Gamma_{\text{sph}}$  reads [58] (see also [61])

$$\Gamma_{\text{sph}} = (25.4 \pm 2.0) \alpha_W^5 T^4 \quad (\text{symmetric phase}), \quad (12)$$

with  $\alpha_W = g^2/4\pi$ . A more refined expression for general  $SU(N)$  can be found in [59]. Recently the sphaleron rate has been calculated numerically throughout the electroweak transition, interpolating between (11) and (12) [60]. For Higgs masses between 100 GeV and 300 GeV, sphaleron reactions in the SM become slower than the rate of the universe's expansion at a temperature  $T_{\text{sph}}$ , with  $100 \text{ GeV} \lesssim T_{\text{sph}} \lesssim 300 \text{ GeV}$  [74]. Above this temperature, baryon number is efficiently violated and all Sakharov conditions are fulfilled. Thus, the SM in principle can provide a framework for baryogenesis.

However, it turns out that both, the violation of  $CP$ , condition II), and the deviation from thermal equilibrium, condition III), are not large enough to produce the observed  $\eta$  (and thus  $\Omega_B$ ). The amount of CP-violation can be estimated by constructing reparametrisation invariant objects out of the quark mass matrices [75, 76]. The lowest order CP-noninvariant combination is the Jarlskog determinant [77], which in terms of quark masses and mixing angles reads

$$D = \sin(\theta_{12}) \sin(\theta_{23}) \sin(\theta_{13}) \delta_{KM} (m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)(m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2). \quad (13)$$

A dimensionless quantity can be constructed when dividing by the relevant temperature  $T_{\text{sph}}$ , at which the BAU freezes out, to the 12<sup>th</sup> power,  $D/T_{\text{sph}}^{12} \sim 10^{-20} \ll \eta$ . Though not a direct proof of impossibility, the smallness of this result makes baryogenesis within the SM very challenging [75, 76, 78–80].

During most of the history of the universe, cosmic expansion is the only source of non-equilibrium. Within the SM, the BAU has to be created around  $T \sim T_{\text{sph}}$ , as otherwise it would be washed out by sphaleron processes. At these temperatures, all particle reactions in the SM act much faster than cosmic expansion (their rates are much larger than the Hubble parameter), keeping all particle species very close to thermal equilibrium. The only way to cause a significant deviation from equilibrium at  $T \sim T_{\text{sph}}$ , necessary to satisfy condition III) [82], would be a first order phase transition from the symmetric to the Higgs phase of the electroweak theory [78]. It proceeds via nucleation of bubbles of new (Higgs) phase. The bubbles expand rapidly, as the field configuration inside is energetically more favourable. The mechanism of baryogenesis related to bubble wall expansion is based on the following picture [83] (for spinodial decomposition phase transition see [84]). When the bubble wall, which separates the symmetric phase from the Higgs phase, passes through the medium, it can cause a large deviation from equilibrium. Due to the CP-violation, the reflection and transmission coefficients for quarks and antiquarks colliding with the bubble wall are different; this allows to generate a matter-antimatter asymmetry, which can dissipate into the bubble. It is preserved in the Higgs phase from washout because sphalerons are inefficient, but disappears in the symmetric phase, where baryon number non-conservation is rapid.

In the electroweak theory the symmetric and the Higgs phases are continuously connected. A first order phase transition could only occur if the Higgs mass were below 72 GeV [85–87]; this is in clear contradiction with experimental data [37], allowing to conclude that it is extremely unlikely that the observed BAU can be generated within the SM.

In the past decade, two clear signs of particle physics beyond the SM other than the BAU have been found experimentally. These are the discovery of neutrino flavour changing processes, usually interpreted as oscillations<sup>12</sup>, and the conclusion that the observed DM cannot be baryonic. The latter is based on BBN and CMB precision data [28, 34], which in combination with accurate measurements of the Hubble parameter [38] and simulations of structure formation show that the amount of matter in the universe exceeds the amount of baryonic matter by a factor  $\sim 6$  [24]. The explanation of these experimental facts unavoidably requires physics beyond the SM. Extensions of the SM generally contain new sources of CP violation and often also  $B$  violation, and there is not much motivation to insist on a source for the BAU within the SM. In section IV.3 we explore the possibility that neutrino oscillations and the observed DM have a common origin that is also responsible for the BAU.

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<sup>12</sup>For a comprehensive review and references to original experimental and theoretical work see [81]

## IV.2 Beyond the SM

Baryogenesis necessarily involves  $B$ -violating processes due to condition I). At the same time, the current non-observation of these, e.g. in proton decay or  $n - \bar{n}$ -oscillations, strongly constrains  $B$ -violation in the present day universe. An enormous number of models that are in accord with these conditions have been suggested since Sakharov. Often they are grouped into those that directly generate a matter-antimatter asymmetry in the baryonic sector and those that initially generate a lepton asymmetry (“leptogenesis”), which is then transferred to the baryonic sector, either by SM sphalerons or processes that involve physics beyond the SM.

One can alternatively classify the variety of models into *top-down* and *bottom-up* approaches. In top down approaches, the underlying theory has usually not been developed for the purpose to explain the BAU, but is motivated by more general theoretical or aesthetic considerations. The most prominent examples are grand unified theories (GUT) and supersymmetry (SUSY), but also string inspired scenarios. The requirement to predict the correct BAU is a necessary condition that can be used to constrain the parameter space for these classes of models.

Bottom-up approaches, on the other hand, take the SM as a basis and add ingredients that allow to explain the BAU. Ideally, these account also for other phenomena that cannot be explained within the SM. A guideline for the exploration of the infinite-dimensional space of possible SM-extensions can be the principle of minimality (“Ockhams razor”), often accompanied by “naturalness” considerations. We discuss a specific model that obeys these principles in section IV.3. Bottom-up models may be viewed as effective field theories, without knowledge of the underlying physics at higher energy scales.

Though theoretically very interesting, most models of baryogenesis are hard to falsify. They may remain viable even if no signals are observed in any experiments in the centuries to come, as they can be saved from falsification by pushing up an associated energy scale. In some cases, indirect evidence that supports the underlying theory may be found in low energy experiments or astrophysical observations, but even then it would be unlikely that these data single out one model and the source of the BAU can be identified uniquely. In foreseeable time, only three of the popular scenarios are testable in the strict sense that all parameters of the theory may be measured: electroweak baryogenesis, resonant leptogenesis [90] and baryogenesis from sterile neutrino oscillations [91, 94]. The former two are covered in other parts [88, 89] of [1], we therefore in the following only discuss baryogenesis from neutrino oscillations.

## IV.3 Baryogenesis from Sterile Neutrino Oscillations

In the SM, neutrinos are the only fermions that appear only as left chiral fields. At the same time, neutrino flavour changing processes, usually interpreted as oscillations, cannot be explained within the model. Complementing the SM by right handed neutrinos that are singlet under all gauge interactions, offers an attractive explanation for neutrino oscillations due to masses generated by the seesaw mechanism [93]. This model is described by the Lagrangian

$$\begin{aligned} \mathcal{L}_{\nu MSM} = & \mathcal{L}_{SM} + i\bar{\nu}_R \not{\partial} \nu_R - \bar{L}_L F \nu_R \tilde{\Phi} - \bar{\nu}_R F^\dagger L_L \tilde{\Phi}^\dagger \\ & - \frac{1}{2}(\bar{\nu}_R^c M_M \nu_R + \bar{\nu}_R M_M^\dagger \nu_R^c), \end{aligned} \quad (14)$$

where we have suppressed flavour and isospin indices.  $\mathcal{L}_{SM}$  is the Lagrangian of the SM.  $F$  is a matrix of Yukawa couplings and  $M_M$  a Majorana mass term for the right handed neutrinos  $\nu_R$ .  $L_L = (\nu_L, e_L)^T$  are the left handed lepton doublets and  $\Phi$  is the Higgs doublet.

The Lagrangian (14), with eigenvalues of  $M_M$  far above the electroweak scale, is the basis of thermal leptogenesis scenarios [92], in which the CP-asymmetry responsible for the BAU is generated during the freezeout and decay of right handed neutrinos. The attractive feature of this setup is that it provides a common explanation for the small neutrino masses and the BAU within GUTs.

For eigenvalues of  $M_M$  below the electroweak scale, the Lagrangian (14) yields the possibility that the asymmetry was created during the thermal production of right handed (sterile) neutrinos in the early universe - rather than during their freezeout and decays [91, 94]. This mechanism was called baryogenesis via (sterile) neutrino oscillations in [91]. It is, however, also efficient when the oscillations are practically not relevant because they are e.g. too rapid and average out. The crucial point is that the initial sterile neutrino abundance deviates from its equilibrium value, and chemical equilibrium is not established before sphaleron freezeout.

This possibility is realised in the *Neutrino minimal Standard Model* ( $\nu$ MSM), which can be viewed as a minimal extension of the SM. This in particular means that there is no modification of the gauge group, the number of fermion families remains unchanged and no new energy scale above the Fermi scale is introduced. It can explain simultaneously three empirical facts that cannot be understood within the framework of the SM: The observed neutrino oscillations, dark matter and the BAU. Here we focus on the latter. An introduction to the  $\nu$ MSM, along with the most recent bounds on its parameter space, can be found in [99], for additional reading see [94–98, 101, 104].

The Lagrangian (14) yields six different neutrino mass eigenstates. Three of them are mixes of the “active” SM neutrinos  $\nu_\alpha$  ( $\alpha = e, \mu, \tau$ ) with masses  $m_i$ . The other three are “sterile” neutrinos  $N_1$ ,  $N_2$  and  $N_3$  with masses  $M_I$ . Mixing between active and sterile neutrinos is suppressed by small angles  $\theta_{\alpha I} = (m_D M_M^{-1})_{\alpha I}$ , where  $m_D = Fv$  and  $v$  is the Higgs expectation value. The mass matrix  $m_\nu$  for the active neutrinos, leading to the observed neutrino oscillations, is generated by the seesaw mechanism [92, 93];  $m_\nu \simeq -\theta M_M \theta^T$ . For eigenvalues of  $M_M$  below the electroweak scale, this requires the Yukawa couplings  $F$  to be tiny.

The requirement to produce the correct BAU can be used to constrain the  $\nu$ MSM parameter space and find the experimentally interesting region. In the following we assume that only two sterile neutrinos  $N_{2,3}$  participate in baryogenesis, which leaves open the possibility to use  $N_1$  as DM candidate. In the simplest scenario,  $N_{2,3}$  are not produced during reheating due to their tiny Yukawa interactions [102]. Instead, they are produced thermally from the primordial plasma during the radiation dominated epoch. Since they are generated as flavour eigenstates, they undergo oscillations. Throughout this nonequilibrium process, all Sakharov conditions are fulfilled and baryogenesis is possible if several requirements are fulfilled. On one hand, the (temperature dependent) mass splitting  $|\delta M| = |M_3 - M_2|/2$  has to be large enough for the neutrinos to perform several oscillations, on the other hand it has to be small to ensure resonant amplification. Finally,  $N_{2,3}$  should not reach chemical equilibrium before sphaleron freezeout to avoid washout.

If the  $\nu$ MSM shall, apart from the BAU, also explain the observed DM density  $\Omega_{DM}$ , the lightest sterile neutrino ( $N_1$ ) is required to be sufficiently long lived to constitute all DM. Then its mixing angle must be too small to be seen in collider experiments. However, being a decaying DM candidate, it can be searched for indirectly by astronomical observations [101]. These, together with the seesaw formula, constrain the  $N_1$  mass to  $1 \text{ keV} \lesssim M_1 \lesssim 50 \text{ keV}$ . This implies that one active neutrino is effectively massless, which fixes the absolute scale of neutrino masses. In contrast,  $N_{2,3}$  can be seen directly at collider experiments [103]. Another consequence of the small

$N_1$  mixing is that its coupling is too small to contribute to the generation of a BAU. Baryogenesis can therefore be described in an effective theory with only two sterile neutrinos  $N_{2,3}$ . CP-violating oscillations amongst them can generate a lepton asymmetry, which can be translated into a BAU by SM sphalerons. It turns out that for  $N_{2,3}$  masses  $M_{2,3} = \bar{M} \mp \delta M$  in the GeV range, which are accessible to direct search experiments, the observed BAU can only be generated when the masses are quasi-degenerate, i.e.  $\delta M \ll \bar{M}$ . The degeneracy is essential for a resonant amplification of the CP-violating effects. If one, however, drops the requirement that the Lagrangian (14) shall also explain the observed DM, all three sterile neutrinos can participate in baryogenesis. It has been found in [100] that in this case, no mass degeneracy is needed due to the additional sources of CP-violation in the couplings of  $N_1$ .

The parameter space can be studied in a quantitative manner by means of effective kinetic equations, similar to those commonly used in neutrino physics [97, 111]. They allow to track the time evolution of the  $N_I$  and lepton chemical potentials. Detailed studies have been performed in [98, 99, 104]. During this calculation one can approximate  $M_1 = 0$  and drop  $N_1$  from the Lagrangian, which has no effect on baryogenesis. This leaves 11 parameters in addition to the SM. In the Casas-Ibarra parametrisation for  $F$  [105], these are three active mixing angles, two active neutrino masses, two Majorana masses  $M \pm \Delta M$  in  $M_M$ , one Dirac phase, one Majorana phase and the real and imaginary part of a complex angle  $\omega$ .

Figure 2 shows the sterile neutrino masses  $\bar{M} \simeq M$  and mixings  $U^2 = \text{tr}(\theta^\dagger \theta)$  for which the observed BAU can be generated by the two sterile neutrinos  $N_{2,3}$ . It also displays other experimental bounds and constraints from BBN. To obtain these results, all known parameters have been fixed to their experimental values found in [51], while the CP-violating phases have been chosen to maximise the lepton asymmetries.

If one requires the  $N_1$  density to make up for the observed  $\Omega_{DM}$ , its thermal production rate needs to be amplified resonantly [106]. The resonant amplification is due to a level crossing between active and sterile neutrino dispersion relations, caused by the MSW effect [112, 113], and requires the presence of a lepton asymmetry  $|N_L - N_{\bar{L}}|/s \gtrsim 8 \cdot 10^{-6}$  in the plasma [107]. This LAU, which exceeds the BAU by orders of magnitude, has to be produced during the freezeout and decay of  $N_{2,3}$ . Such large asymmetry can only be generated from  $N_{2,3}$  oscillations if their masses are highly degenerate, with a physical mass splitting  $\delta M$  of the order of active neutrino masses  $m_i$  [98]. This degeneracy is much stronger than the one required to explain the BAU. Thus, the BAU and DM production in the  $\nu$ MSM are both related to lepton asymmetries in the early universe, produced by the same sources of CP-violation. This may hint to understand the similarity  $\Omega_{DM} \sim \Omega_B$ , though it does not provide an obvious explanation because today's values of  $\Omega_B$  and  $\Omega_{DM}$  depend on several other parameters. The requirement to generate a sufficient LAU allows to impose further constraints on the sterile neutrino properties. This was included in the analysis in [98, 99]. The computational effort for quantitative studies is huge, as it requires to track time evolution from hot big bang initial conditions down to temperatures  $\sim 100$  MeV, below hadronisation. At different temperatures, different processes enter the effective Hamiltonian. Various time scales, related to production, oscillations, decoherence, freezeout and decay of the  $N_I$  are involved. A detailed study has been performed in [98, 99].

Currently, the main uncertainty in these results comes from the kinetic equations. The BAU is generated from a quantum interference, in a regime where coherent oscillations can be essential. The semiclassical kinetic equations known from neutrino physics most likely capture the main features of this process, but may require corrections in the resonant regime. A first principles derivation [120, 122] is required to determine the size of these. This is not entirely specific to the

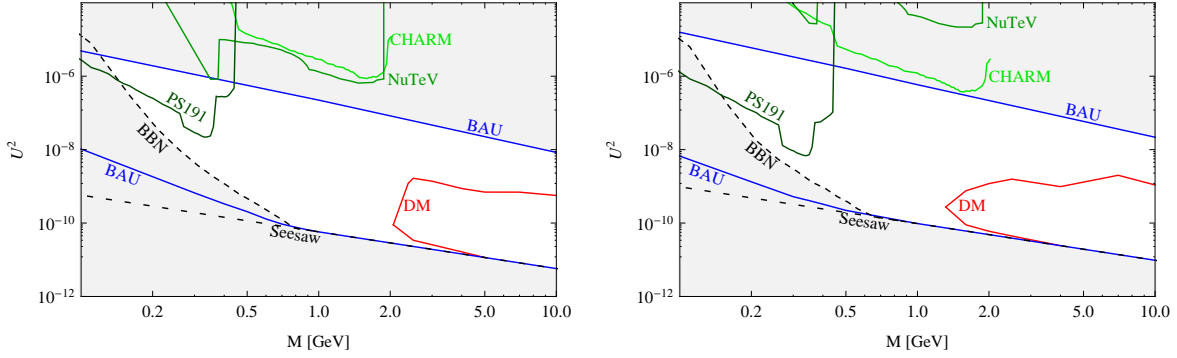


Figure 2: Constraints on sterile neutrino mass  $M$  and mixing  $U^2 = \text{tr}(\theta^\dagger \theta)$  in the  $\nu\text{MSM}$  as found in [98, 99] for normal (left panel) and inverted (right panel) hierarchy of active neutrino masses. In the regions below the black dashed "seesaw" line there exists no choice of  $\nu\text{MSM}$  parameters that is in accord with experimental constraints on the active neutrino mixing matrix. In the region below the black dotted BBN line, the lifetime of  $N_{2,3}$  particles in the early universe is larger than 0.1s, yielding the danger that their decay spoils the agreement between BBN calculations and observed light element abundances. The regions above the green lines of different shade are excluded by the NuTeV [108], CHARM [109] and CERN PS191 [110] experiments, as indicated in the plot. In the region between the blue lines, a CP-asymmetry that explains the observed BAU can be produced during the thermal production of  $N_{2,3}$ . In the region within the red line, thermal production of  $N_1$  (resonant and non-resonant) is sufficient to explain all observed DM. The CP-violating phases that maximise the efficiency of baryogenesis and DM production are different. They were chosen independently for the blue and red line displayed here. The region in which  $\Omega_B$  and  $\Omega_{DM}$  can be explained simultaneously almost coincides with the area inside the red line, see [99].

$\nu\text{MSM}$ ; a consistent description of transport phenomena involving quantum interference, flavour effects and CP-violation remains an active field of research in many scenarios of baryogenesis [114–128].

## V Conclusions

The origin of matter remains one of the great mysteries in physics. Observationally we can be almost certain that the present day universe contains no significant amounts of (baryonic) antimatter, and the baryons are the remnant of a small matter-antimatter asymmetry  $\sim 10^{-10}$  in the early universe. This asymmetry cannot be explained within the Standard Model of particle physics and cosmology. It provides, along with neutrino oscillations, dark matter and accelerated cosmic expansion, one of the few observational proofs of physics beyond the SM. Many extensions of the SM are able to explain the BAU. However, since it is characterised by only one observable number, the BAU cannot be used to pin down the correct model realised in nature. In spite of that, it provides a necessary condition that can be used to exclude or constrain models, and baryogenesis remains a very active field of research. Amongst the many suggested theories of baryogenesis, only a few are experimentally testable. We discussed an example of this kind, in which right handed neutrinos are the common origin of the BAU, DM and neutrino oscillations.

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## References

- [1] New J. Phys Focus Issue on the Origin of Matter (New J. Phys. **14** (2012) 095012).
- [2] P. A. M. Dirac, Proc. Roy. Soc. Lond. A **117** (1928) 610.
- [3] C. D. Anderson, Science **76** (1932) 238; C. D. Anderson, Phys. Rev. **43** (1933) 491.
- [4] A. Friedman Z.Phys **10** (1): 377386 (1922).
- [5] G. Lemaître, Annales de la Societe Scientifique de Bruxelles, **A47**, 49-59 (1927);
- [6] E. Hubble, Proc. Nat. Acad. Sci. **15** (1929) 168.
- [7] A. A. Penzias and R. W. Wilson, Astrophys. J. **142** (1965) 419; R. H. Dicke, P. J. E. Peebles, P. G. Roll and D. T. Wilkinson, Astrophys. J. **142** (1965) 414.
- [8] G. Gamow, Phys. Rev. **70** (1946) 572; R. A. Alpher, H. Bethe and G. Gamow, Phys. Rev. **73** (1948) 803.
- [9] C. S. Wu, E. Ambler, R. W. Hayward, D. D. Hoppes and R. P. Hudson, Phys. Rev. **105** (1957) 1413.
- [10] J. H. Christenson, J. W. Cronin, V. L. Fitch and R. Turlay, Phys. Rev. Lett. **13** (1964) 138.
- [11] A. D. Sakharov, Pisma Zh. Eksp. Teor. Fiz. **5** (1967) 32 [JETP Lett. **5** (1967) 24] [Sov. Phys. Usp. **34** (1991) 392] [Usp. Fiz. Nauk **161** (1991) 61].
- [12] V. A. Kuzmin, Pisma Zh. Eksp. Teor. Fiz. **12** (1970) 335.
- [13] A. A. Starobinsky, Phys. Lett. B **91** (1980) 99; A. H. Guth, Phys. Rev. D **23** (1981) 347; A. D. Linde, Phys. Lett. B **108** (1982) 389; A. Albrecht and P. J. Steinhardt, Phys. Rev. Lett. **48** (1982) 1220.
- [14] V. A. Kuzmin, V. A. Rubakov and M. E. Shaposhnikov, Phys. Lett. B **155** (1985) 36; V. A. Rubakov and M. E. Shaposhnikov, Usp. Fiz. Nauk **166** (1996) 493 [Phys. Usp. **39** (1996) 461] [hep-ph/9603208].
- [15] G. 't Hooft, Phys. Rev. Lett. **37** (1976) 8.
- [16] M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49** (1973) 652.
- [17] G. Steigman, Ann. Rev. Astron. Astrophys. **14** (1976) 339.
- [18] F. W. Stecker, Nucl. Phys. B **252** (1985) 25.
- [19] G. Steigman, JCAP **0810** (2008) 001 [arXiv:0808.1122 [astro-ph]].
- [20] J. Alcaraz *et al.* [AMS Collaboration], Phys. Lett. B **461** (1999) 387 [hep-ex/0002048].
- [21] C. Bambi and A. D. Dolgov, Nucl. Phys. B **784** (2007) 132 [astro-ph/0702350].
- [22] A. G. Cohen, A. De Rujula and S. L. Glashow, Astrophys. J. **495** (1998) 539 [astro-ph/9707087].
- [23] A. G. Cohen and A. De Rujula, astro-ph/9709132.
- [24] O. Lahav and A. Liddle, arXiv:1002.3488 [astro-ph.CO], published in K. Nakamura *et al.* [Particle Data Group Collaboration], J. Phys. G G **37** (2010) 075021.

- [25] O. Reimer, M. Pohl, P. Sreekumar and J. R. Mattox, *Astrophys. J.* **588** (2003) 155 [astro-ph/0301362].
- [26] A. C. Edge, G. C. Stewart, A. C. Fabian, A. K. Arnaud, *MNRAS* **245**, 559 (1990)
- [27] M. Markevitch, A. H. Gonzalez, L. David, A. Vikhlinin, S. Murray, W. Forman, C. Jones and W. Tucker, *Astrophys. J.* **567** (2002) L27 [astro-ph/0110468].
- [28] B. Fields and S. Sarkar, *J. Phys. G* **33** (2006) 1 [astro-ph/0601514].
- [29] G. Steigman, arXiv:1008.4765 [astro-ph.CO].
- [30] B. D. Fields, *Annual Review of Nuclear and Particle Science*, 61, **47-68** (2011) [arXiv:1203.3551 [astro-ph.CO]].
- [31] G. Mangano, G. Miele, S. Pastor, T. Pinto, O. Pisanti and P. D. Serpico, *Nucl. Phys. B* **729** (2005) 221 [hep-ph/0506164].
- [32] J. Hamann, S. Hannestad, G. G. Raffelt, I. Tamborra and Y. Y. Y. Wong, *Phys. Rev. Lett.* **105** (2010) 181301 [arXiv:1006.5276 [hep-ph]]; J. Hamann, *JCAP* **1203** (2012) 021 [arXiv:1110.4271 [astro-ph.CO]].
- [33] J. Dunkley, R. Hlozek, J. Sievers, V. Acquaviva, P. A. R. Ade, P. Aguirre, M. Amiri and J. W. Appel *et al.*, *Astrophys. J.* **739**, 52 (2011) [arXiv:1009.0866 [astro-ph.CO]]; R. Keisler, C. L. Reichardt, K. A. Aird, B. A. Benson, L. E. Bleem, J. E. Carlstrom, C. L. Chang and H. M. Cho *et al.*, *Astrophys. J.* **743**, 28 (2011) [arXiv:1105.3182 [astro-ph.CO]]; B. A. Benson, T. de Haan, J. P. Dudley, C. L. Reichardt, K. A. Aird, K. Andersson, R. Armstrong and M. Bautz *et al.*, arXiv:1112.5435 [astro-ph.CO].
- [34] E. Komatsu *et al.* [WMAP Collaboration], *Astrophys. J. Suppl.* **192** (2011) 18 [arXiv:1001.4538 [astro-ph.CO]].
- [35] R. I. Epstein, J. M. Lattimer and D. N. Schramm, *Nature* **263** (1976) 198.
- [36] W. J. Percival *et al.* [SDSS Collaboration], *Mon. Not. Roy. Astron. Soc.* **401** (2010) 2148 [arXiv:0907.1660 [astro-ph.CO]].
- [37] G. Aad *et al.* [ATLAS Collaboration], *Phys. Lett. B* **710** (2012) 49 [arXiv:1202.1408 [hep-ex]]; S. Chatrchyan *et al.* [CMS Collaboration], *Phys. Lett. B* **710** (2012) 26 [arXiv:1202.1488 [hep-ex]]; S. Chatrchyan *et al.* [CMS Collaboration], *Phys. Lett. B* **716** (2012) 30 [arXiv:1207.7235 [hep-ex]]; G. Aad *et al.* [ATLAS Collaboration], *Phys. Lett. B* **716** (2012) 1 [arXiv:1207.7214 [hep-ex]].
- [38] A. G. Riess, L. Macri, S. Casertano, M. Sosey, H. Lampeitl, H. C. Ferguson, A. V. Filippenko and S. W. Jha *et al.*, *Astrophys. J.* **699** (2009) 539 [arXiv:0905.0695 [astro-ph.CO]].
- [39] V. Simha and G. Steigman, *JCAP* **0806** (2008) 016 [arXiv:0803.3465 [astro-ph]].
- [40] H. -S. Kang and G. Steigman, *Nucl. Phys. B* **372** (1992) 494; S. H. Hansen, G. Mangano, A. Melchiorri, G. Miele and O. Pisanti, *Phys. Rev. D* **65** (2002) 023511 [astro-ph/0105385]; G. Mangano, G. Miele, S. Pastor, O. Pisanti and S. Sarikas, *JCAP* **1103** (2011) 035 [arXiv:1011.0916 [astro-ph.CO]]; V. Simha and G. Steigman, *JCAP* **0808** (2008) 011 [arXiv:0806.0179 [hep-ph]].
- [41] G. Mangano, G. Miele, S. Pastor, O. Pisanti and S. Sarikas, *Phys. Lett. B* **708** (2012) 1 [arXiv:1110.4335 [hep-ph]].
- [42] E. Castorina, U. Franca, M. Lattanzi, J. Lesgourgues, G. Mangano, A. Melchiorri and S. Pastor, *Phys. Rev. D* **86** (2012) 023517 [arXiv:1204.2510 [astro-ph.CO]].

- [43] A. D. Dolgov, S. H. Hansen, S. Pastor, S. T. Petcov, G. G. Raffelt and D. V. Semikoz, Nucl. Phys. B **632** (2002) 363 [hep-ph/0201287].
- [44] Y. Y. Y. Wong, Phys. Rev. D **66** (2002) 025015 [hep-ph/0203180].
- [45] K. N. Abazajian, J. F. Beacom and N. F. Bell, Phys. Rev. D **66** (2002) 013008 [astro-ph/0203442].
- [46] S. Pastor, T. Pinto and G. G. Raffelt, Phys. Rev. Lett. **102** (2009) 241302 [arXiv:0808.3137 [astro-ph]].
- [47] F. P. An *et al.* [DAYA-BAY Collaboration], Phys. Rev. Lett. **108** (2012) 171803 [arXiv:1203.1669 [hep-ex]].
- [48] J. K. Ahn *et al.* [RENO Collaboration], Phys. Rev. Lett. **108** (2012) 191802 [arXiv:1204.0626 [hep-ex]].
- [49] G. L. Fogli, E. Lisi, A. Marrone, D. Montanino, A. Palazzo and A. M. Rotunno, Phys. Rev. D **86** (2012) 013012 [arXiv:1205.5254 [hep-ph]].
- [50] D. J. Schwarz and M. Stuke, JCAP **0911** (2009) 025 [Erratum-ibid. **1010** (2010) E01] [arXiv:0906.3434 [hep-ph]].
- [51] G. L. Fogli, E. Lisi, A. Marrone, A. Palazzo and A. M. Rotunno, Phys. Rev. D **84** (2011) 053007 [arXiv:1106.6028 [hep-ph]]; T. Schwetz, M. Tortola and J. W. F. Valle, New J. Phys. **13** (2011) 109401 [arXiv:1108.1376 [hep-ph]].
- [52] M. Shaposhnikov, *Anomalous fermion number nonconservation.*, preprint CERN-TH.6304-91, C91-06-17, lecture given at *1991 Summer School in High Energy Physics and Cosmology: Trieste, Italy 17 June-9 August*, published in ICTP Series in Theoretical Physics (Trieste HEP Cosmol.1991:338-374), ISBN-10: 9810210183, ISBN-13: 978-9810210182 available online from <http://cds.cern.ch/record/1000000/files/9202054>
- [53] S. Y. Khlebnikov and M. E. Shaposhnikov, Nucl. Phys. B **308**, 885 (1988).
- [54] S. L. Adler, Phys. Rev. **177** (1969) 2426; J. S. Bell and R. Jackiw, Nuovo Cim. A **60** (1969) 47.
- [55] C. G. Callan, Jr., R. F. Dashen and D. J. Gross, Phys. Lett. B **63** (1976) 334.
- [56] R. Jackiw and C. Rebbi, Phys. Rev. Lett. **37** (1976) 172.
- [57] F. R. Klinkhamer and N. S. Manton, Phys. Rev. D **30** (1984) 2212.
- [58] D. Bodeker, G. D. Moore and K. Rummukainen, Phys. Rev. D **61** (2000) 056003 [hep-ph/9907545]; G. D. Moore, hep-ph/0009161.
- [59] G. D. Moore and M. Tassler, JHEP **1102** (2011) 105 [arXiv:1011.1167 [hep-ph]].
- [60] M. D'Onofrio, K. Rummukainen and A. Tranberg, JHEP **1208** (2012) 123 [arXiv:1207.0685 [hep-ph]].
- [61] H. P. Shanahan and A. C. Davis, Phys. Lett. B **431** (1998) 135 [hep-ph/9804203]; G. D. Moore, Phys. Rev. D **62** (2000) 085011 [hep-ph/0001216].
- [62] P. B. Arnold and L. D. McLerran, Phys. Rev. D **36** (1987) 581.
- [63] J. Kunz, B. Kleihaus and Y. Brihaye, Phys. Rev. D **46** (1992) 3587.
- [64] G. D. Moore, Phys. Rev. D **53** (1996) 5906 [hep-ph/9508405].
- [65] T. Akiba, H. Kikuchi and T. Yanagida, Phys. Rev. D **40** (1989) 588.

- [66] L. Carson and L. D. McLerran, Phys. Rev. D **41** (1990) 647.
- [67] L. Carson, X. Li, L. D. McLerran and R. -T. Wang, Phys. Rev. D **42** (1990) 2127.
- [68] J. Baacke and S. Junker, Phys. Rev. D **49** (1994) 2055 [hep-ph/9308310]; J. Baacke and S. Junker, Phys. Rev. D **50** (1994) 4227 [hep-th/9402078].
- [69] P. B. Arnold and O. Espinosa, Phys. Rev. D **47** (1993) 3546 [Erratum-ibid. D **50** (1994) 6662] [hep-ph/9212235].
- [70] Z. Fodor and A. Hebecker, Nucl. Phys. B **432** (1994) 127 [hep-ph/9403219].
- [71] K. Farakos, K. Kajantie, K. Rummukainen and M. E. Shaposhnikov, Nucl. Phys. B **425** (1994) 67 [hep-ph/9404201].
- [72] P. B. Arnold, D. Son and L. G. Yaffe, Phys. Rev. D **55** (1997) 6264 [hep-ph/9609481].
- [73] G. D. Moore, Phys. Rev. D **59** (1999) 014503 [hep-ph/9805264].
- [74] Y. Burnier, M. Laine and M. Shaposhnikov, JCAP **0602** (2006) 007 [hep-ph/0511246].
- [75] M. E. Shaposhnikov, Nucl. Phys. B **299** (1988) 797.
- [76] T. Brauner, O. Taanila, A. Tranberg and A. Vuorinen, Phys. Rev. Lett. **108** (2012) 041601 [arXiv:1110.6818 [hep-ph]].
- [77] C. Jarlskog, Phys. Rev. Lett. **55** (1985) 1039.
- [78] M. E. Shaposhnikov, JETP Lett. **44** (1986) 465 [Pisma Zh. Eksp. Teor. Fiz. **44** (1986) 364]; M. E. Shaposhnikov, Nucl. Phys. B **287** (1987) 757.
- [79] J. Ambjorn, M. L. Laursen and M. E. Shaposhnikov, Nucl. Phys. B **316** (1989) 483.
- [80] G. R. Farrar and M. E. Shaposhnikov, Phys. Rev. D **50** (1994) 774 [hep-ph/9305275]; M. B. Gavela, P. Hernandez, J. Orloff, O. Pene and C. Quimbay, Nucl. Phys. B **430** (1994) 382 [hep-ph/9406289]; P. Huet and E. Sather, Phys. Rev. D **51** (1995) 379 [hep-ph/9404302]; G. R. Farrar and M. E. Shaposhnikov, [hep-ph/9406387].
- [81] for a comprehensive review and references to original experimental and theoretical work see A. Strumia and F. Vissani, hep-ph/0606054.
- [82] A. D. Dolgov, Pisma Zh. Eksp. Teor. Fiz. **29** (1979) 254.
- [83] A. E. Nelson, D. B. Kaplan and A. G. Cohen, Nucl. Phys. B **373** (1992) 453; A. G. Cohen, D. B. Kaplan and A. E. Nelson, Ann. Rev. Nucl. Part. Sci. **43** (1993) 27 [hep-ph/9302210].
- [84] L. D. McLerran, M. E. Shaposhnikov, N. Turok and M. B. Voloshin, Phys. Lett. B **256** (1991) 451.
- [85] K. Kajantie, M. Laine, K. Rummukainen and M. E. Shaposhnikov, Phys. Rev. Lett. **77** (1996) 2887 [hep-ph/9605288].
- [86] K. Rummukainen, M. Tsypin, K. Kajantie, M. Laine and M. E. Shaposhnikov, Nucl. Phys. B **532** (1998) 283 [hep-lat/9805013].
- [87] F. Csikor, Z. Fodor and J. Heitger, Phys. Rev. Lett. **82** (1999) 21 [hep-ph/9809291].
- [88] D. E. Morrissey and M. J. Ramsey-Musolf, arXiv:1206.2942 [hep-ph].

- [89] S. Blanchet and P. Di Bari, arXiv:1211.0512 [hep-ph].
- [90] A. Pilaftsis, Phys. Rev. D **56** (1997) 5431 [hep-ph/9707235]; A. Pilaftsis, Int. J. Mod. Phys. A **14** (1999) 1811 [hep-ph/9812256]. A. Pilaftsis and T. E. J. Underwood, Nucl. Phys. B **692** (2004) 303 [hep-ph/0309342]; A. Pilaftsis and T. E. J. Underwood, Phys. Rev. D **72** (2005) 113001 [hep-ph/0506107].
- [91] E. K. Akhmedov, V. A. Rubakov and A. Y. Smirnov, Phys. Rev. Lett. **81** (1998) 1359 [arXiv:hep-ph/9803255].
- [92] M. Fukugita and T. Yanagida, Phys. Lett. B **174** (1986) 45.
- [93] P. Minkowski, Phys. Lett. B **67**, 421 (1977); T. Yanagida, Progr. Theor. Phys. **64** 1103 (1980); M. Gell-Mann, P. Ramond and R. Slansky, in *Supergravity*, North Holland, Amsterdam 1980; R. N. Mohapatra and G. Senjanovic, Phys. Rev. Lett. **44** 912 (1980).
- [94] T. Asaka and M. Shaposhnikov, Phys. Lett. B **620** (2005) 17 [hep-ph/0505013].
- [95] M. Shaposhnikov, JHEP **0808** (2008) 008 [arXiv:0804.4542 [hep-ph]].
- [96] T. Asaka and H. Ishida, Phys. Lett. B **692** (2010) 105 [arXiv:1004.5491 [hep-ph]].
- [97] T. Asaka, S. Eijima and H. Ishida, JCAP **1202** (2012) 021 [arXiv:1112.5565 [hep-ph]].
- [98] L. Canetti, M. Drewes and M. Shaposhnikov, arXiv:1204.3902 [hep-ph].
- [99] L. Canetti, M. Drewes, T. Frossard and M. Shaposhnikov, arXiv:1208.4607 [hep-ph].
- [100] M. Drewes and B. Garbrecht, arXiv:1206.5537 [hep-ph].
- [101] A. Boyarsky, O. Ruchayskiy and M. Shaposhnikov, Ann. Rev. Nucl. Part. Sci. **59** (2009) 191 [arXiv:0901.0011 [hep-ph]].
- [102] F. Bezrukov, D. Gorbunov and M. Shaposhnikov, JCAP **0906** (2009) 029 [arXiv:0812.3622 [hep-ph]].
- [103] D. Gorbunov and M. Shaposhnikov, JHEP **0710** (2007) 015 [arXiv:0705.1729 [hep-ph]].
- [104] L. Canetti and M. Shaposhnikov, JCAP **1009** (2010) 001 [arXiv:1006.0133 [hep-ph]].
- [105] J. A. Casas and A. Ibarra, Nucl. Phys. B **618** (2001) 171 [hep-ph/0103065].
- [106] X. -D. Shi and G. M. Fuller, Phys. Rev. Lett. **82** (1999) 2832 [astro-ph/9810076].
- [107] M. Laine and M. Shaposhnikov, JCAP **0806** (2008) 031 [arXiv:0804.4543 [hep-ph]].
- [108] A. Vaitaitis *et al.* [NuTeV and E815 Collaborations], Phys. Rev. Lett. **83** 4943 (1999).
- [109] F. Bergsma *et al.* [CHARM Collaboration], Phys. Lett. B **166** 473 (1986).
- [110] G. Bernardi, G. Carugno, J. Chauveau, F. Dicarolo, M. Dris, J. Dumarchez, M. Ferro-Luzzi and J. M. Levy *et al.*, Phys. Lett. B **166** 479 (1986), G. Bernardi, G. Carugno, J. Chauveau, F. Dicarolo, M. Dris, J. Dumarchez, M. Ferro-Luzzi and J. -M. Levy *et al.*, Phys. Lett. B **203** 332 (1988).
- [111] G. Sigl and G. Raffelt, Nucl. Phys. B **406** (1993) 423.
- [112] L. Wolfenstein, Phys. Rev. D **17**, (1978) 2369.
- [113] S. P. Mikheev and A. Y. Smirnov, Sov. J. Nucl. Phys. **42**, (1985) 913 [Yad. Fiz. **42**, (1985) 1441].
- [114] W. Buchmuller and S. Fredenhagen, Phys. Lett. B **483** (2000) 217.

- [115] T. Prokopec, M. G. Schmidt and S. Weinstock, *Annals Phys.* **314** (2004) 208; T. Prokopec, M. G. Schmidt and S. Weinstock, *Annals Phys.* **314** (2004) 267.
- [116] A. De Simone and A. Riotto, *JCAP* **0708** (2007) 002.
- [117] A. Anisimov, W. Buchmuller, M. Drewes and S. Mendizabal, *Annals Phys.* **324** (2009) 1234 [arXiv:0812.1934 [hep-th]]; M. Drewes, arXiv:1012.5380 [hep-th]; M. Drewes, S. Mendizabal and C. Weniger, arXiv:1202.1301 [hep-ph].
- [118] A. Anisimov, W. Buchmuller, M. Drewes and S. Mendizabal, *Annals Phys.* **326** (2011) 1998; A. Anisimov, W. Buchmuller, M. Drewes and S. Mendizabal, *Phys. Rev. Lett.* **104** (2010) 121102.
- [119] M. Garny, A. Hohenegger, A. Kartavtsev and M. Lindner, *Phys. Rev. D* **81** (2010) 085027 [arXiv:0911.4122 [hep-ph]]; M. Garny, A. Hohenegger, A. Kartavtsev and M. Lindner, *Phys. Rev. D* **80** (2009) 125027 [arXiv:0909.1559 [hep-ph]]; M. Garny, A. Hohenegger and A. Kartavtsev, *Phys. Rev. D* **81** (2010) 085028 [arXiv:1002.0331 [hep-ph]]; M. Garny, A. Hohenegger and A. Kartavtsev, arXiv:1005.5385 [hep-ph];
- [120] M. Garny, A. Kartavtsev and A. Hohenegger, arXiv:1112.6428 [hep-ph].
- [121] M. Beneke, B. Garbrecht, M. Herranen and P. Schwaller, *Nucl. Phys. B* **838** (2010) 1 [arXiv:1002.1326 [hep-ph]]; M. Beneke, B. Garbrecht, C. Fidler, M. Herranen and P. Schwaller, *Nucl. Phys. B* **843** (2011) 177; B. Garbrecht, *Nucl. Phys. B* **847** (2011) 350 [arXiv:1011.3122 [hep-ph]].
- [122] B. Garbrecht and M. Herranen, *Nucl. Phys. B* **861** (2012) 17 [arXiv:1112.5954 [hep-ph]].
- [123] V. Cirigliano, C. Lee, M. J. Ramsey-Musolf and S. Tulin, *Phys. Rev. D* **81** (2010) 103503 [arXiv:0912.3523 [hep-ph]].
- [124] M. Herranen, K. Kainulainen and P. M. Rahkila, *JHEP* **1012** (2010) 072 [arXiv:1006.1929 [hep-ph]]; M. Herranen, K. Kainulainen and P. M. Rahkila, *JHEP* **1202** (2012) 080 [arXiv:1108.2371 [hep-ph]]; C. Fidler, M. Herranen, K. Kainulainen and P. M. Rahkila, *JHEP* **1202** (2012) 065 [arXiv:1108.2309 [hep-ph]].
- [125] J. M. Cline, M. Joyce and K. Kainulainen, *JHEP* **0007** (2000) 018 [hep-ph/0006119].
- [126] B. Garbrecht and M. Garny, *Annals Phys.* **327** (2012) 914 [arXiv:1108.3688 [hep-ph]].
- [127] B. Garbrecht, *Phys. Rev. D* **85** (2012) 123509 [arXiv:1201.5126 [hep-ph]].
- [128] J. -S. Gagnon and M. Shaposhnikov, *Phys. Rev. D* **83** (2011) 065021 [arXiv:1012.1126 [hep-ph]].